

The preservation of last-glacial (>50 to 40 ka) colluvium on low-relief surfaces in Alishan, an actively uplifting mountain in southwestern Taiwan

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ARTICLE INFO

Article history:

Received 5 May 2018

Received in revised form 29 August 2018

Accepted 30 August 2018

Available online 31 August 2018

Keywords:

Low-relief surface

Climate change

Landslide

Taiwan orogen

ABSTRACT

Geomorphic studies on the Taiwan orogen have long focused on the rapid erosion and efficient sediment transport in response to active tectonic uplift and frequent earthquakes/heavy rains. Little attention has been paid to the common low-relief surfaces in high mountains that appear to have been geomorphically stable for a long period of time. We undertook a study on a group of such gentle surfaces in Alishan, which consist of poorly drained hummocky slopes averaging 15° and as wide as 2 km. These gentle slopes are underlain by mass-wasting gravels 60–100 m thick, from which 22 radiocarbon dates >50 to 40 ka BP in age were obtained. Below these thick colluvial deposits are ~20° bedrock bedding planes apparently exposed by dip-slope failures. Combining these data reveals alternating hillslope erosion and deposition, along with episodic river downcutting, at a time scale of several 10⁴ yr. We relate this temporal change in geomorphic processes to glacial-interglacial climate change. During the wet inter-/post-glacial periods characterized by frequent heavy rains, landslides/debris flows prevailed and rivers were capable of conveying most sediment eroded from hillslopes. Frequent debris flows combined with sufficient bedload sediments serving as tools for fluvial erosion caused rapid river downcutting. In contrast, the low river erosion/transport capacity during the dry last-glacial period allowed progressive deposition of thick colluvium on the preexisting, gentle bedding surfaces probably eroded during the last interglacial period. This study shows how glacial-interglacial climate change influenced the river/hillslope processes and landscape evolution of the Taiwan orogen.

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1. Introduction

The Taiwan orogen (Fig. 1) has been considered an example of non-glaciated mountain belts with the tectonic uplift balanced by erosion, achieving a topographic steady state, with elevations limited to 4000 m despite eroding rapidly for millions of years (Suppe, 1981; Willett et al., 2003; Stolar et al., 2007). Geomorphic studies of Taiwan's mountains, influenced by this perception and with clear evidence of the strong impact of earthquakes/heavy rains, have long emphasized the rapid erosion and efficient sediment transport on steep slopes (e.g., Hovius et al., 2000; Dadson et al., 2003; Lin et al., 2009) and along bedrock rivers (e.g., Hartshorn et al., 2002; Schaller et al., 2005; Yanites et al., 2010; Cook et al., 2013). However, little attention has been paid to the common gentle topographies exhibiting rounded crests, hummocky slopes, alluvial surfaces, or low-gradient meandering chan-

nels stranded in high mountains that appear to have been geomorphically stable for a long period of time. These low-relief, high-elevation topographies (or surfaces) were recognized by Japanese researchers a century ago (Lin, 1957). In that era, dominated by Davis's cycle of erosion (Davis, 1899), the juxtaposition of these gentle surfaces with surrounding steep slopes was believed indicative of alternate cessation and rejuvenation of tectonism that drove episodic river planation and downward incision, respectively (Lin, 1957). Since then, and long after the decline of Davis's theory, no additional hypotheses have been proposed to address the origin of these landscapes.

Perhaps the main reason why these low-relief, high-elevation surfaces have long been ignored is the scarcity of outcrops to study. In addition, most of these topographies are located in remote inaccessible areas. So far, neither constitutive nor chronological data of these landscapes have been reported.

This study explores in detail for the first time low-relief topographies in the high mountains of Taiwan, focusing on the Alishan area (Fig. 1). The area is known for its large stretches of conifer forests, including one of the most famous tourist attractions in Taiwan: the Alishan forest recreation park (hereafter the Alishan Park). The forests consisted of

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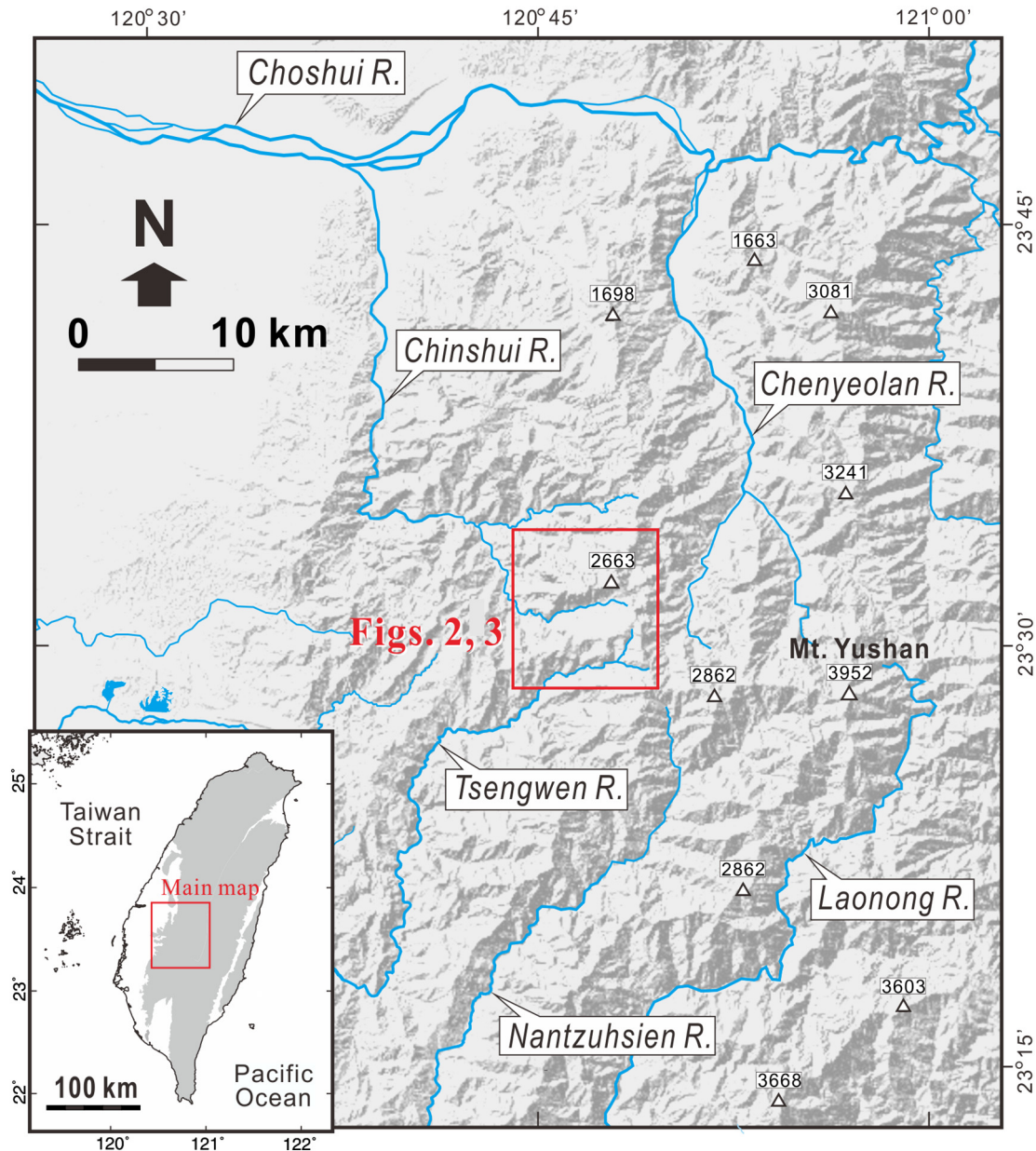


Fig. 1. Shaded relief map of central-southwestern Taiwan and the location of the Alishan area (in the rectangle). Inset shows the geographic position of Taiwan with hill/mountain areas shaded.

numerous, very large red cypress trees, evidence of the millennial geomorphic stability of the area. It was not until the erosion brought by Typhoon Morakot in 2009 that some deep-seated colluvium was exposed. We examined the sedimentary features of this colluvium and obtained >30 radiocarbon dates. These, along with the topographic features, allowed us to reconstruct landscape histories, estimate bedrock incision rates, and interpret their significance. Most of the dates obtained are >40 ka. They are expressed as radiocarbon ages (designated BP). The remaining dates (<7 ka) are converted to 1σ calibrated age ranges (designated cal BP) and calibrated using the Bayesian calibration programme OxCal (Rev 7.0.4, Bronk Ramsey, 2001, 2009) utilizing the Northern Hemisphere calibration curve IntCal 13 (Reimer et al., 2013). Although this study focuses on landscape evolution at a local site, the results help us understand how climate changes at glacial-interglacial scales could control mass-wasting and fluvial processes in shaping active mountains as in Taiwan.

2. Study area

2.1. Geological and geomorphic settings

The Alishan, located west of the Yushan (at 3952 m, the highest elevation in Taiwan), refers to the <3000-m high mountain area from which the Chinshui/Chenyeolan rivers flow to the north and the Tsengwen River to the south (Fig. 1). The area is underlain by Miocene shallow marine sedimentary rocks. The younger Kuantoushan sandstone and the older Nanchuan formation (sandstone/shale) strike generally southwest and dip 10–30° to the north (Fig. 2). As a part of the Taiwan orogen, the tectonic uplift of the area started no earlier than ~5 million years ago (e.g., Teng, 1990). Based on apatite fission-track dating from the Chenyeolan River ~10 km north of the study area (Fuller et al., 2006), the denudation rate of the region is estimated to be 2–4 mm yr⁻¹ in the past 1–2 million years. The area is currently uplifted at rates up to

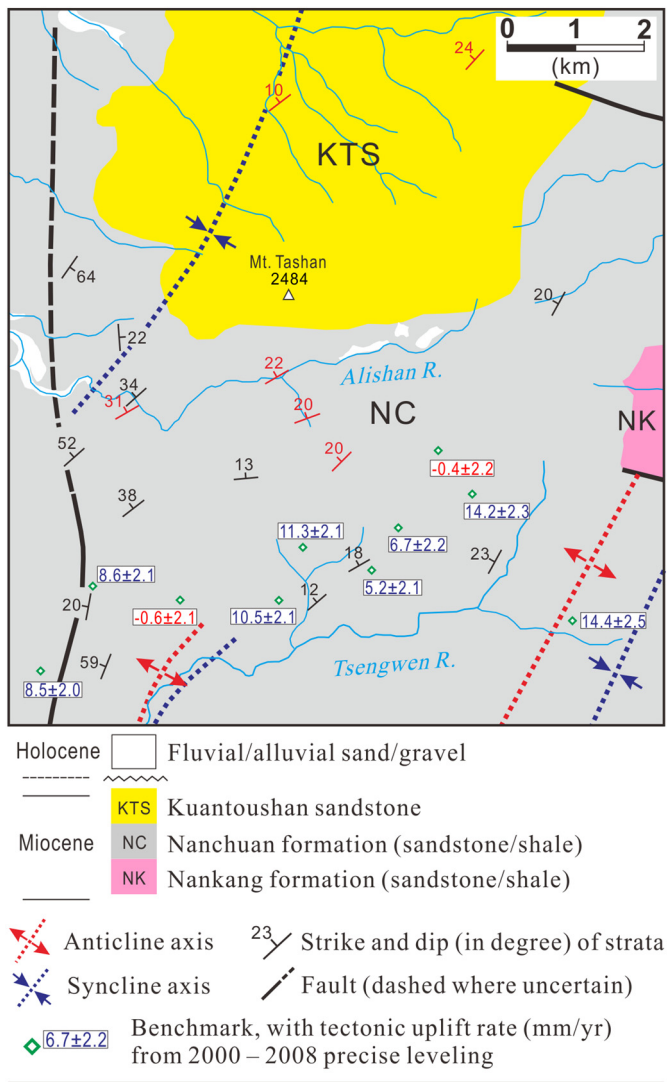


Fig. 2. Geological map of the Alishan area, modified from Chinese Petroleum Corporation (1986). For location see Fig. 1. Strike/dip data in red are surveyed in this study. Also shown are current tectonic uplift rates based on 2000–2008 precise leveling data (Ching et al., 2011). Note the two negative rates (in red) apparently reflecting mass wasting.

14 mm yr⁻¹ (mostly >8 mm yr⁻¹), according to leveling surveys across its southern part (Fig. 2) (Ching et al., 2011).

The attitude of the rock formations apparently controls the topography of the region, as almost all of the hillslopes dipping north or west are much wider and gentler than those dipping south or east (Figs. 3 and 4). These relatively gentle slopes can be grouped into two broad, low-relief surfaces, the Tashan surface in the north and the Alishan surface in the south, separated by the Alishan River, the upstream portion of the Chishui River (Figs. 3 and 4). The Tashan surface, underlain by the Kuantoushan sandstone, includes some abandoned alluvial surfaces and is deeply dissected by rivers flowing to the north. The Alishan surface (Fig. 5a and b), underlain by the Nanchuan formation, is characterized by poorly drained hummocky slopes of apparently mass-wasting origin. This study focuses on the Alishan surface and its bounding Alishan River, as they offered better exposures to study.

The Tashan surface is bounded to the south by a prominent cliff, the Tashan cliff, along the north bank of the Alishan River (Figs. 3 and 4). This cliff exhibits multiple landslide scarps cutting the thick Kuantoushan sandstone and is 700–1000 m high where it fringes the ridge connecting Mt. Datashan (2663 m) and Mt. Tashan (2484 m) of the Tashan surface

(Fig. 5c and d). A truncated valley serving as the headwaters of a north-flowing river cutting the Tashan surface exists on this ridge (Fig. 3).

The Alishan has a monsoon climate and receives annual rainfall of 3000–5000 mm, most of which comes from summer monsoons or tropical typhoons that commonly bring daily rainfalls of >500 mm. The area is also subject to fog cover (>100 days per year), which facilitates the growth of Taiwan red cypress (*Chamaecyparis formosensis*), a conifer with a long life span that formed impressive forests of giant trees commonly 3–2 ka in age (e.g., Chan and Huang, 2015). Logging of these forests began in the early twentieth century with the construction of mountain railways for transportation. The logging ceased in 1965 and the forests have been restored, with the railways used for tourism purposes.

2.2. Recent geomorphic changes

The 1999 Chichi earthquake ($M_w = 7.6$) occurring in central Taiwan destroyed the main train station in the Alishan Park and triggered many landslides in the region. A branch of the mountain railway system, the Mianyu railway, was cut by a landslide from Datashan Mountain. More landslides and debris flows occurred after the earthquake, mainly along the Tsengwen River and the lower/middle parts of the Alishan River. The mass movements culminated during Typhoon Morakot (7–10 August 2009), which delivered a record 2800 mm of rain in the area. The Mianyu railway was cut again by a landslide (named the Datashan; Fig. 5d) generated from the same site as the 1999 landslide. This landslide also produced debris flows downslope along a tributary (labelled A) of the Alishan River (Fig. 3).

The largest landslide (named the Erhwanping) triggered by the 2009 typhoon in Alishan took place at a north-dipping slope facing the Alishan River, drained by a tributary labelled C (Fig. 3). This landslide, with the main scarp located close to the ridge top, has a source area 600–700 m high, 800 m wide, and a volume of $1.3 \times 10^7 \text{ m}^3$ (Lee et al., 2012). It damaged the train station of Erhwanping and, ~300 m below, eroded away a 600 m-long section of the railway east of Pingthema train station (Fig. 6). A part of the landslide then ran along a relatively narrow valley before entering the Alishan River and generating debris flows there (Figs. 3 and 6).

The Erhwanping is known as an area prone to landslides. The area is named for its distinctive flat surface that had an area of $6.6 \times 10^4 \text{ m}^2$ and served as a lumber distribution center in the early twentieth century (Chen, 2008). This flat surface, however, was reduced to $\sim 5.6 \times 10^4 \text{ m}^2$ by a rainfall-induced landslide in 1912. An earthquake (Chungpu) in 1941 demolished the train station and caused the collapse of the surface by $7 \times 10^3 \text{ m}^2$. The 1999 Chichi earthquake did not cause erosion in the area, but after the 2009 typhoon the surface was reduced to $1.7 \times 10^4 \text{ m}^2$, a quarter of its original area (Chen, 2008).

The 2009 typhoon triggered two additional notable landslides in the study area. One, labelled X (Figs. 3 and 7), occurred southwest of Erhwanping, from the middle part of a south-dipping slope facing the Tsengwen River. It eroded an area ~150 m high, cutting the highway to the Alishan Park before running into a tributary of the Tsengwen River (Fig. 7). Another landslide, labelled Y, was generated on a north-dipping slope bounding the middle-lower course of the Alishan River (Figs. 3 and 7). The landslide was up to 250 m high and involved the failure of the entire hillslope from the crest downward, depositing debris that formed a hummocky slope at the toe. More minor landslides were generated, especially in the middle and lower parts of the Alishan River catchment, with debris flows emanating from almost all tributaries joining this part of the trunk river.

3. The Alishan surface

3.1. Topography

This group of hummocky surfaces comprises several parts separated by tributary valleys or by relatively steep slopes >50 m high (Fig. 3). The

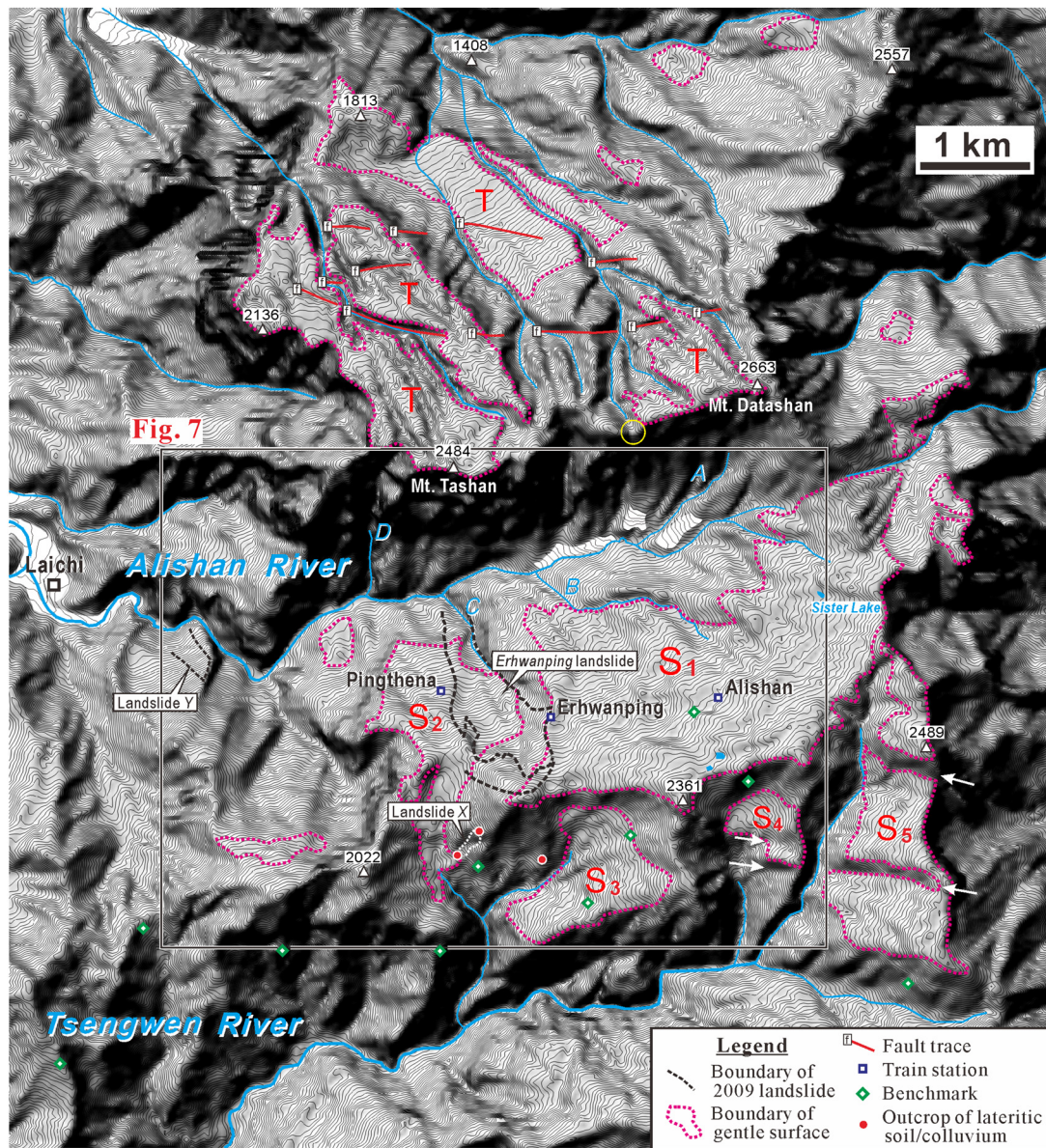


Fig. 3. Contoured, shaded-relief map of the Alishan area, constructed by 40-m mesh DEM issued by the Ministry of the Interior (based on data around 1980s). For location see Fig. 1. Contour intervals at 10 m. T: Tashan surface (undifferentiated); S1 – S5: Alishan surface. Circled is a beheaded valley on the main drainage divide. Arrows point to east-striking linear escarpments truncating Surfaces S4 and S5. Also exhibited are locations of benchmarks for leveling surveys and sites where lateritic soils/colluvium cropped out.

broadest and the highest surface (labelled S1), dipping northwestward from the divide between the Alishan and Tsengwen rivers, encircles the uppermost part of the Alishan River (Fig. 7). It comprises multiple hummocky surfaces bounded by arc-shaped scarps <30 m high and has an average slope of 15°, which is somewhat gentler than the underlying bedrock bedding planes nearby (dipping around 20°). The drainage networks on the surface are commonly disconnected with ponds developed in local depressions (including the scenic Sister Lake in the Alishan Park; Fig. 3). Continuous channels are exhibited only on the lower parts of the surface. These channels incise the surface and show prominent knickpoints where joining the trunk Alishan River.

To the west, a lower surface (labelled S2), including the area of Pingthana, straddles the Alishan/Tsengwen drainage divide (Fig. 7). A large portion of this surface facing the Alishan River was eroded away by the 2009 Erhwanping landslide, which originated from the slope connecting this surface with the higher S1 surface. Downslope from the eroded railway east of Pingthana, Surfaces S1 and S2 are separated by a southeast-striking escarpment with Tributary C flowing along the

base (Figs. 3 and 5b). This escarpment exhibits thick sandstone beds, with some waterfall steps developed along the lower part of Tributary C. Two major sets of nearly vertical joints are shown, trending west-east and northwest-southeast. The former is parallel to the Tashan cliff; the latter is consistent with the trend of the escarpment.

More hummocky surfaces, labelled S3, S4, and S5, are exhibited along the northern side of the Tsengwen River (Fig. 3). Surfaces S3 and S4 are fringed with the main drainage divide by a cliff, which exhibits multiple landslide scarps, like other cliffs in the study area. To the east and separated by a tributary valley is Surface S5, which extends to the drainage divide with the Chenyeolan River. Both the S4 and S5 surfaces are cut by some 50–100-m high, east-striking linear escarpments (Fig. 3). It should be noted that although the regional hillslope dips to the south, formed by the downward incision of the Tsengwen River, the hummocky surfaces here dip generally to the west or northwest. Only the northern parts of Surfaces S3 and S4 below the main drainage divide comprise south-dipping surfaces, apparently formed by colluvial deposition (Fig. 7).

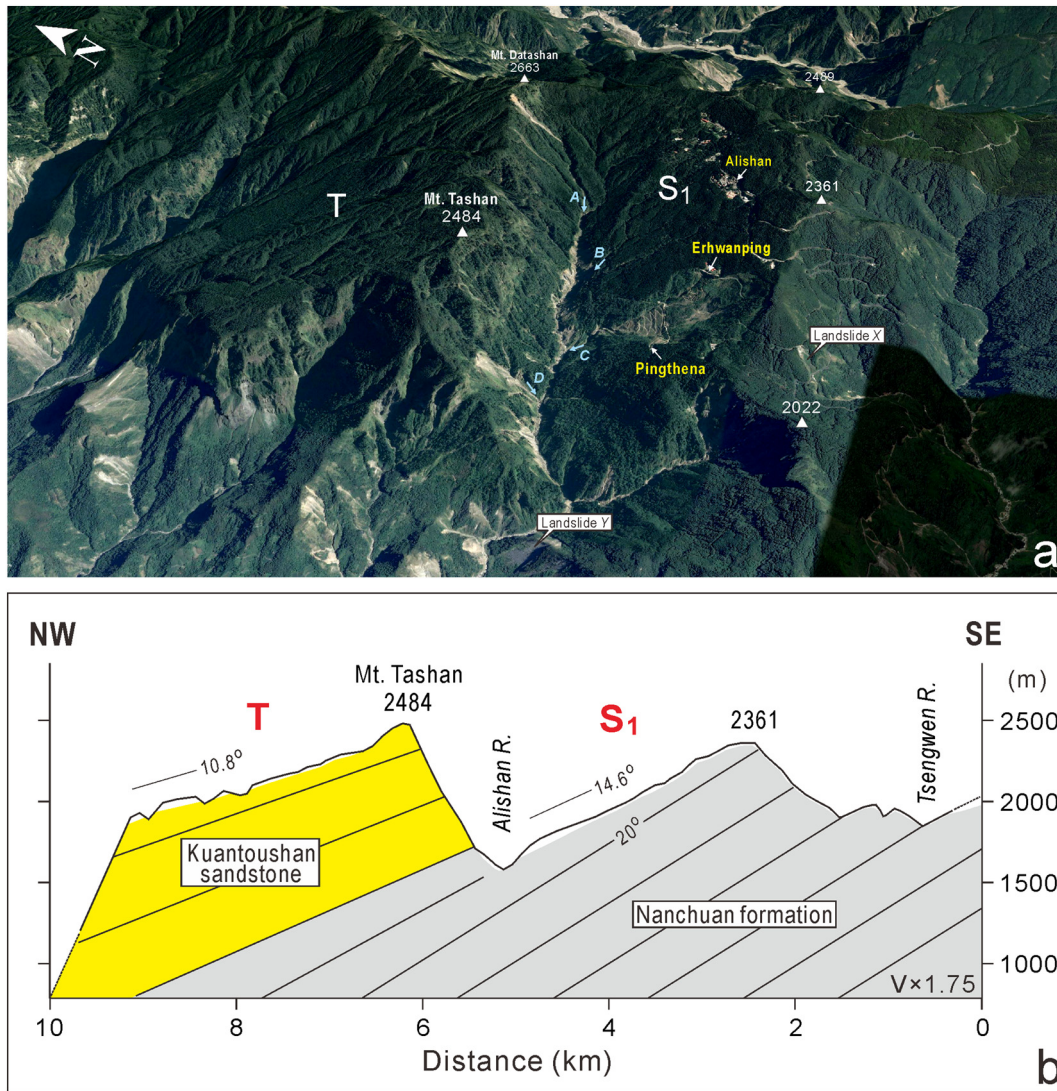


Fig. 4. Topography of the Alishan area. (a) Google Earth 3-D satellite image (date: 2 December 2015), no vertical exaggeration. White arrow points to train station; blue arrow denotes the downstream-most course of tributary (see also Fig. 3). Note that the 2009 Erhwanping landslide (between Erhwanping and Pingthema train stations) has been remediated by engineering works. (b) Transverse profile trending N34°W, with Mt. Tashan and Mt. 2361 included. Rock formations in Fig. 2 are shown, with diagonal lines signifying generalized bedding planes.

3.2. Sedimentary features and chronology

Giant boulders (or bedrock blocks), subangular to subrounded in shape and up to several meters in diameter, are commonly found on the hummocky surfaces in the study area. These surfaces are capped by poorly-stratified, yellow colored and heavily-weathered colluvial gravels along gullies, roads, and railways entrenched into the ground surface. The erosion brought by the 2009 landslides also revealed remnants of lateritic soils and reddish colluvium underlying some slopes facing the Tsengwen River (Figs. 3 and 7). The reddish colluvium exposed along the scarp of Landslide X is commonly mixed with yellowish colluvium, with the red-colored muddy materials probably sourced from lateritic soils (Fig. 8). Many gravel clasts in these deposits also have been heavily weathered and can easily be scraped across concrete roads to produce red-colored streaks (Fig. 8c). Similar mixtures of yellowish and reddish gravels >20 m thick were also exposed where Landslide X cut Surface S2 in the downslope direction (Fig. 8d). Notably, no such reddish colluvium has been found in the Alishan River catchment.

The erosion by the 2009 landslides also revealed thick colluvial gravels below the hillslopes facing the Alishan River (Fig. 9). The Erhwanping landslide revealed that the site of Erhwanping train station (Surface S1)

was underlain by colluvial gravels >60 m thick (Fig. 9a). Even the relatively steep source area of the landslide exhibited >50-m thick colluvium after the erosion by the landslide. The exposed colluvial gravels consist mostly of cobble- or boulder-sized clasts including angular to subrounded giant boulders. Most of these gravels are rich in grey-colored muds and exhibit matrix-supported textures (Fig. 9). Those below Erhwanping are ~20 m thick and show transitional boundaries with the surrounding yellowish gravels (Fig. 9a). The greyish gravels exposed upslope of Pingthema (>10 m thick) are truncated and capped by yellowish, clast-supported gravels a few meters thick (Fig. 9b, c). All these greyish gravels contain abundant, mostly non-carbonized, wood remnants (Fig. 9d). They have been dated $46,369 \pm 1389$ BP at Erhwanping (Site 1, below Surface S1) and >50 ka BP (seven dates) upslope of Pingthema (Sites 2–4, below Surface S2) (Table 1; Figs. 6 and 7). Two of these >50 ka BP dates are derived from samples collected on the surfaces of the Erhwanping landslide (Sites 3 and 4).

Similar greyish, wood-bearing gravels also outcropped below the lower part of Surface S1, along a tributary (labelled B) of the Alishan River. They yielded four dates, ranging from $45,548 \pm 1107$ to $41,321 \pm 740$ BP (Sites 5 and 6; Fig. 7). These greyish gravels, like those constituting Surface S2 upslope of Pingthema, have a sharp



Fig. 5. Scenes of Alishan. (a) The broadest gentle slope (Surface S1). Viewed to the west (from the Mianyue railway); yellow arrow points to Alishan train station. The 2009 Erhwanping landslide in the distance; white arrow shows the moving direction. (b) Surface S1 and its bounding escarpment, viewed to the east (from the western flank of the Erhwanping landslide). Yellow line on the escarpment traces the bedrock bedding plane below colluvium. (c) The Tashan cliff, viewed from Erhwanping train station. (d) The Tashan cliff and the 2009 Datashan landslide, viewed from the Alishan forest recreation park. Arrow points to the rock shed tunnel of the Mianyue railway.

boundary with the overlying yellowish gravels (Fig. 9e). On the other side of the ridge facing the Tsengwen River, patches of greyish gravels were exposed by a tributary cutting Surface S3 as mixtures with yellowish gravels (Fig. 9f). Here, a date of >50 ka BP was obtained (Site 7; Fig. 7).

4. The Alishan River

4.1. Topography

The Alishan River originates from Surface S1 and incises it deeply downstream (Figs. 3 and 10). The uppermost part of the trunk river above the junction with Tributary A, surrounded by dense forest, is characterized by cascade or step-pool topographies built typically by rounded, moss-veneered boulders up to 2 m in diameter (Fig. 11a). The river significantly steepens, with an accumulation of numerous subrounded giant boulders >2 m in diameter, near the mouth of Tributary A (Fig. 11b). From here to the tributary junction (~100 m from the mouth of Tributary A), the trunk river was dry during our visits when the weather was fine. In contrast, the lowermost part of Tributary A, gentler and covered by finer-grained gravels, constantly supplied running water to the trunk river. This tributary does not exhibit bedrock waterfalls at or near the river mouth, unlike others entering the upper/middle parts of the trunk river (e.g., Fig. 11c).

Along the lower part of Tributary A, an alluvial/colluvial terrace 10–50 m high is present (labelled T in Fig. 7), extending downstream to near the confluence with Tributary B. Farther downstream, a distinct waterfall ~20 m high is developed (labelled WF; Figs. 7 and 11d) along a river reach with more or less uniform bedrock lithology. Tributary C, which drains the area of the 2009 Erhwanping landslide, enters immediately downstream of this waterfall. From here to Landslide Y, the river flows mainly within a gorge (Fig. 11e). Above this gorge and opposite to the S2 surface, remnants of relatively gentle slopes are preserved along

the lower part of the Tashan cliff (Figs. 7 and 11f). These slopes, higher than Surface S2 but lower than S1, appear to have connected upslope with Surface S1 before the incision of the river (Fig. 10). The river gradually widens after flowing out of the gorge and exhibits >50-m wide floodplains with 10–50-m high terraces downstream from Laichi (Fig. 3).

During the 2009 typhoon, debris flows emanated from tributaries A, C, and others entering the gorge portion of the trunk river. These debris flows left a series of debris terraces (generally <10 m high), especially around the mouths of the tributaries from which they emanated. Angular/subangular giant boulders, commonly >2 m in diameter, were scattered along the river. Between the giant boulders were finer-grained sandy/gravelly bars, chaotic or organized, apparently deposited by minor debris flows or fluvial processes after the major debris-flow surges. All these features are in great contrast with those along the uppermost part of the trunk river above the junction with Tributary A.

4.2. Sedimentary features and chronology

Pre-2009 colluvial/alluvial gravels underlying hillslopes or terraces capped by forests, outcropped extensively along the river. Bedrock, commonly separated from the overlying colluvium by bedding planes (Fig. 11c), was only exposed downstream from the middle point between the mouths of Tributaries A and B. The thickness of the colluvial sediment below the outer part of Surface S1 is estimated as great as ~100 m, constrained by the heights of the exposed bedrock. The exposed bedrock generally increased in height above the riverbed in the downstream direction. Along the gorge, thick colluvial sediment was observed only at tributary mouths or within some shallow embayments along the trunk river. However, high above the gorge, colluvial gravels >50 m thick were found underlying the remnants of the gentle slopes stranded along the lower part of the Tashan cliff (Fig. 11f).



Fig. 6. The 2009 Erhwanping landslide, viewed from Mt. Tashan (taken on August 2012). For location see Fig. 3. Arrows point respectively to Erhwanping and Pingthena train stations, which have a relief of ~280 m. Terrace I was created during 2009 Typhoon Morakot. Sites of radiocarbon dates with ages are also shown (see also Fig. 7).

A great portion of the exposed colluvial/alluvial gravels are grey in color (Figs. 12 and 13). Many of them contain abundant greyish mud and wood fragments, similar to those exposed around Erhwanping and Pingthena. These distinct greyish gravels have yielded multiple dates >40 ka. Four of them, ranging from $43,000 \pm 936$ to $41,730 \pm 701$ BP, were derived below the Datashan landslide, associated with the proximal part of Terrace T (Site 9; Figs. 7 and 12a). Here, the terrace exhibited bipartite sedimentary sequences. The lower part consists of massive, matrix-supported greyish gravels ~20 m thick (Fig. 12b). The upper part, up to 30 m thick, comprises fairly-stratified yellowish gravels intercalated with some greyish gravel sheets. The four 44–41 ka BP dates were derived from the lower part. Immediately downstream of the mouth of Tributary A, a date of $41,452 \pm 882$ BP was obtained from the north (right) bank of the trunk river (Site 10; Fig. 7). Two hundred meters downstream from the junction with Tributary B (Site 12; Fig. 7), a block of greyish gravel on the modern riverbed yielded a date of $46,295 \pm 1785$ BP. More dates of >50 ka, >45 ka, and $47,423 \pm 2820$ BP, in an ascending stratigraphic order, were obtained below the gentle-slope remnants fringing the lower part of the Tashan cliff, along a tributary (labelled D) (Site 14; Figs. 7 and 12d).

In addition to the 44–41 ka BP dates, the proximal part of Terrace T also yielded two dates of 6950–6860 and 6500–6450 cal BP (Site 9; Fig. 7), from the surface of a scree slope emanating from the upper part of the terrace. The 6950–6860 cal BP date was sampled from a large, partly carbonized wood fragment; the 6500–6450 cal BP date, from a small non-carbonized wood piece within a block of greyish gravel. Both samples must have been eroded from the upper part of the terrace, although their corresponding stratigraphic positions are unclear. Three almost identical dates, 6490–6410, 6490–6410, and 6550–6460 cal BP, were also derived immediately downstream of the mouth of Tributary A (Site 10; Figs. 7 and 12c), from the side of the river opposite to where the $41,452 \pm 882$ BP date was obtained.

The greyish gravels also yielded multiple dates <3 ka. One of them, 2750–2730 cal BP, was derived from the uppermost part of the trunk river, from a local terrace (~5 m high) at the south (left) bank (Site 8; Fig. 7). A date of 900–740 cal BP was obtained from a block of greyish gravel, ~300 m upstream of the junction with Tributary B (Site 11; Fig. 7). At the lowest part of Tributary C, a date of 500–330 cal BP was yielded from the base of a ~50-m thick gravel sequence apparently deposited by a pre-2009 landslide originating from Erhwanping

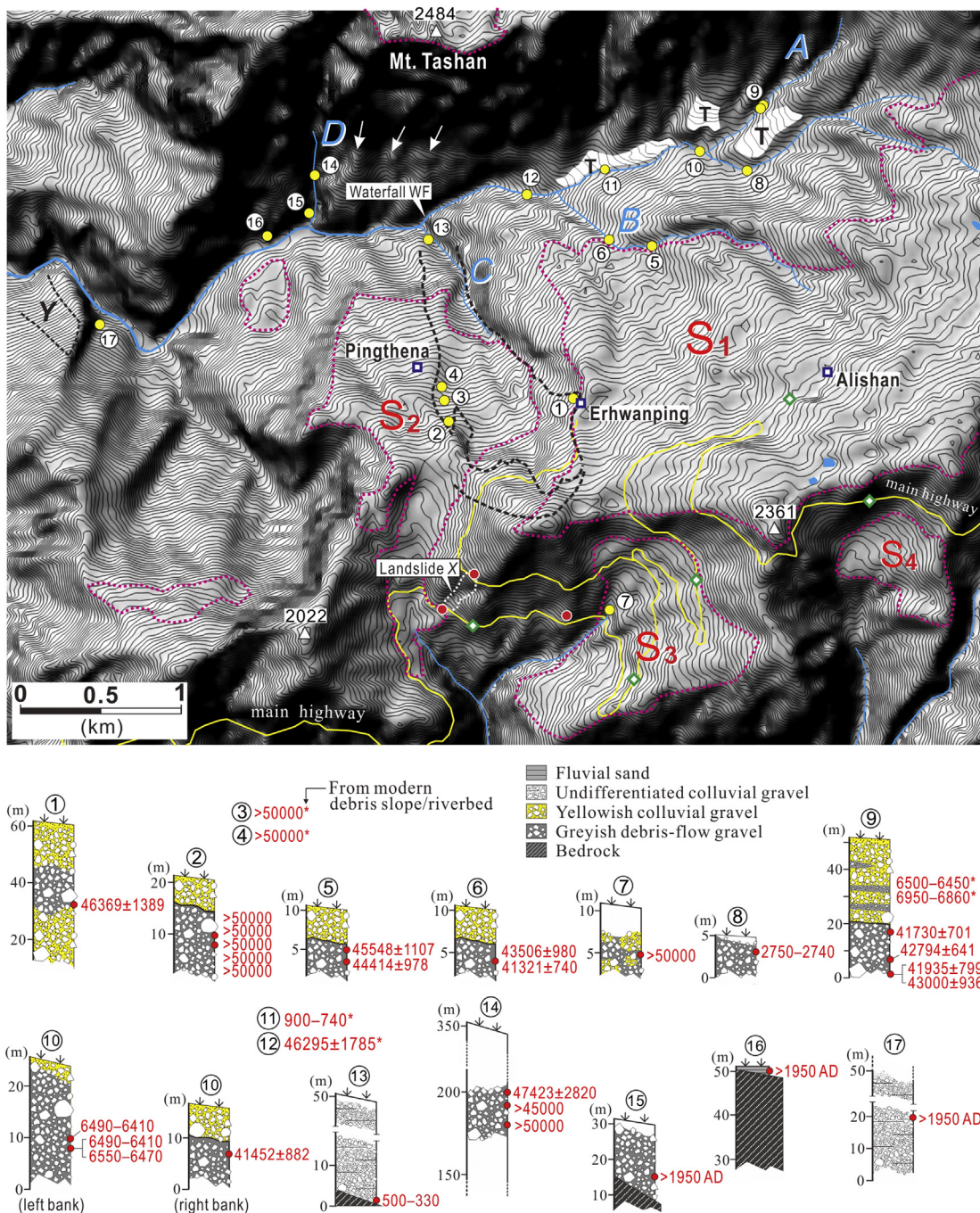


Fig. 7. Summary of stratigraphic and chronological data in this study (see also Table 1). For map location and legend see Fig. 3. Arrows below Mt. Tashan point to remnants of gentle, colluvial slopes preserved at the lower part of the cliff. Radiocarbon dates (in red) >40 ka are expressed as conventional radiocarbon ages (unit: BP). Those <7 ka are converted to 1 σ calibrated age ranges (unit: cal BP). Heights of stratigraphic columns (in meter) are relative to tributary riverbeds except No. 8, 10, 14–17 which are relative to the trunk riverbed.

(Site 13; Figs. 6 and 7). Within the gorge, dates younger than 1950 CE (i.e., containing bomb carbon) were obtained from three sites: a ~20-m thick gravelly debris-flow deposit at the mouth of Tributary D (Site 15; Fig. 7), a 2-m thick muddy sand bed stranded ~50-m high above the valley bottom (Site 16; Figs. 7 and 13a), and a >50 m-thick colluvial sequence 1.2 km farther downstream (Site 17; Figs. 7 and 13b).

Although no chronological data are available, the colluvial gravel exposed along the flank of Landslide Y is noteworthy (Fig. 13c). This landslide, leaving an extensive bedrock bedding plane (~30°) in the source area, is apparently of a dip-slope type (Fig. 13d). The western flank of the landslide cut bedrock, apparently following a set of nearly

vertical joints trending northwest. The eastern flank of the landslide exhibited a wedge-shaped gravel mass that was up to 20 m thick at the toe of the slope and tapered off upward (Fig. 13d).

5. Synthesis and discussion

5.1. Mass-wasting histories

The existence of thick colluvial gravel has revealed ancient mass movements in the Alishan area. At least parts of these movements were deep-seated, supplying enormous amounts of greyish, non-weathered



Fig. 8. Reddish colluvium exposed around Landslide X (for location see Figs. 3 and 7). (a) Along the road crossing the landslide scarp. (b) A close view of the road-cut outcrop, showing the mixture of yellowish gravel clasts with reworked lateritic soils. (c) A sliced lateritic sandstone cobble, which can easily be scraped across the concrete road to produce red-colored streaks. (d) A mixture of yellowish, brownish, and reddish colluvial gravels exposed where the landslide cut Surface S2.

clasts downslope. Debris flows were involved, resulting in the deposition of disorganized gravels rich in muddy matrix. The inclusion of abundant wood fragments in the debris-flow deposits implies damage to forests. The incorporation of subrounded giant boulders, which are likely to have been abraded in fluvial environments, suggests the destruction of drainage networks. All these lines of evidence point to the catastrophic nature of the mass movements. On the basis of as many as 22 dates from multiple sites, these mass movements occurred in a time period of >50–40 ka BP and, given the wide range of the dates, probably included more than one event.

We recognize that 12 of the dates mentioned above, within 50–40 ka BP, are close to the age limit of the radiocarbon dating methods. Considering the quantity of the dates and that they are all derived from large wood samples, we believe these dates are not significantly biased by contamination of modern carbon into the dated samples. The attainment of stratigraphically consistent dates from >50 ka to $47,423 \pm 2820$ BP from a common profile below the Tashan cliff (Site 14; Fig. 7) further reinforces the reliability of the dates and leads us to consider that all the >50 ka dates derived are probably only slightly beyond the age limit of the dating methods (perhaps within 60–50 ka BP).

Our data imply that after 40 ka, erosion took place on the slopes facing the Alishan River, resulting in the prevalence of erosional surfaces truncating the ≥ 40 ka BP deposits. These erosional surfaces are all capped by relatively thin, yellowish colluvium, which is likely to have been sourced from surficial, weathered clasts with deposition rates lower than those of the gravels beneath. This suggests the mass wasting that created the observed hummocky topographies on the studied gentle surfaces occurred relatively slowly and/or infrequently.

Note that our dates (50–40 ka BP) obtained from the higher S1 surface are all younger than those (>50 ka BP) from the S2 (Figs. 7 and 10). This implies that the observed >50–40 ka BP mass-wasting sediment was deposited more or less continuously, so that the strata exhibited at lower elevations are older than those at higher elevations. The

contrast between the elevations of the S1 and S2 surfaces then requires that after the deposition, S2 was eroded and lowered more rapidly than S1. This interpretation is consistent with the occurrence of the 2009 Erhwanping landslide, which significantly lowered the S2 but not S1 (Fig. 7).

According to our data, it was not until 6.9–6.4 ka cal BP (more likely 6.5–6.4 ka cal BP) that mass movements from Mt. Datashan brought significant deposition along the upper part of the Alishan River, forming Terrace T. Other mass-wasting events (~2.7 ka and ~0.8 ka cal BP) are found along this part of the river, but their resulting landforms and depositional records are minor.

The youngest mass-wasting events are all found along the middle-lower part of the Alishan River. At the mouth of Tributary C, a ~0.4 ka landslide from Erhwanping deposited gravelly colluvial deposits thicker than those brought by the 2009 event (Fig. 6). In the downstream direction, a 50-m high sand bed is dated younger than 1950 CE (Site 16; Fig. 7). We consider this sand to have been deposited when the gorge was dammed, with the deposition of the thick colluvium younger than 1950 CE downstream causing this damming (Site 17; Fig. 7). We suspect this event occurred during the 1959 Tropical Storm 081 (August 7–9; induced by Typhoon Ellen), which is second only to 2009 Typhoon Morakot in causing rainfall disasters in the recorded histories of Taiwan.

5.2. Controls of rock structures

The control of bedrock structures on the hillslope morphology of Alishan is shown by its asymmetric valley cross sections (Fig. 3). The processes shaping the wider and gentler north-dipping slopes must have been different from those shaping the slopes dipping south. The similarity in attitudes between the low-relief, hummocky surfaces and the underlying bedrock bedding planes may suggest a dip-slope origin for the surfaces. These surfaces are not typical of dip slopes however, as they are underlain by colluvial sediments of great thicknesses. We

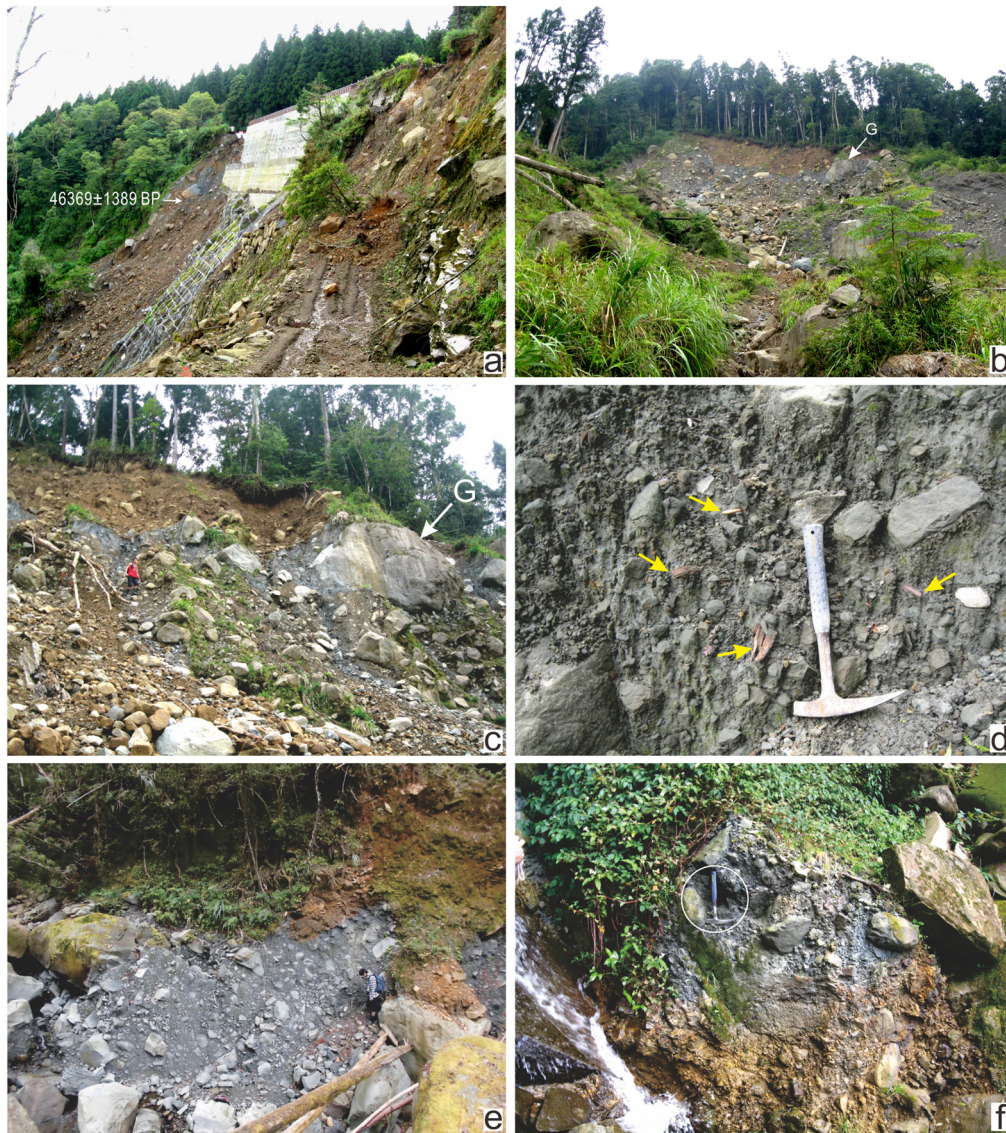


Fig. 9. Colluvium underlying Alishan surface (for location see Fig. 7). All taken in the summer of 2012. (a) Below the Erhwanping train station (Site 1). The retaining wall (~30 m high) and other slope works were constructed after 2009 Typhoon Morakot. (b) Below the slope ~160 m high above Pingthema train station (Site 2), a distant view. (c) Site 2, a relatively close view. Note a subrounded giant boulder (labelled G) nearly 10 m in diameter. (d) A close view of the greyish gravel in (c). Arrows point to non-carbonized wood fragments. (e) Along the left bank of Tributary B (Site 6). (f) Along a tributary of the Tsengwen River cutting Surface S3 (Site 7). A hammer (circled) for scale.

believe this characteristic reflects bidirectional roles of the observed bedding planes on hillslope development. In conditions that the toes of hillslopes were cut, causing “daylight” of bedding planes, dip-slope failures dominated. The existence of these movements is manifested by the common appearance of bedding planes serving as boundaries between bedrock and colluvium. On the other hand, once the erosion stopped, the gentleness of the bedding planes (i.e., the former slide surfaces) facilitated sediment accumulation, allowing the deposition of thick colluvium eroded from the upper parts of hillslopes.

The existence of high-angle joints parallel to hillslope dips is also significant, as they could serve as lateral boundaries of landslides such as that flanking Landslide Y (Fig. 13d). The escarpment separating Surfaces S1 and S2 (Fig. 5b) is also likely to have originated this way. Slope failures with lateral boundaries following such high-angle joints created local depressions (i.e., accommodation) on hillslopes, which could determine where the thickest colluvial sediments could accumulate.

Landslide Y provides an example of how the hillslope processes inferred above may have operated (Fig. 13d). This landslide moved

along a set of bedding planes (~30°) and was flanked in the west by a nearly vertical joint. Parts of the landslide debris ran into the river and was conveyed away by debris flows, with the remaining debris deposited at the toe of the hillslope. It is possible that as long as the toe of the hillslope remains uneroded, more and more sediment would be able to accumulate on the slide surface (bedding plane) to form a colluvial mass similar to that exposed along the eastern flank of the landslide. Note that the colluvial mass exhibited here thins upward and has a surface gentler than the bedrock bedding planes (Fig. 13d). This feature is consistent with the available data that the observed low-relief, hummocky surfaces appear to be slightly gentler than the underlying bedrock bedding planes.

Landslide Y is relatively small, however. For the broad S1 and S2 surfaces to be created, it would be necessary, over long time frames, for dip-slope movements from the north-dipping hillslopes to force the trunk Alishan River to shift to the north in association with the downward incision of the river. A positive feedback mechanism may have operated, as the north-dipping hillslopes, once enlarged, could generate more extensive dip-slope failures, which in turn enhanced the

Table 1

Radiocarbon dates obtained in this study (all from wood fragments).

Site ^a	¹⁴ C age	Lab. no ^b (yr BP)	Calibrated age ^c (cal yr BP)	Height ^d (m)	Note
1	46,369 ± 1389	Wk-39013	–	32	
2	>50,000	NTU-5758	–	10	
	>50,000	NTU-5773	–	10	
	>50,000	Wk-39012	–	10	
	>50,000	NTU-5736	–	8	
	>50,000	NTU-5744	–	8	
3	>50,000	NTU-5775	–	–	Sample on modern debris slope
4	>50,000	NTU-5743	–	–	Sample on modern debris slope
5	45,548 ± 1107	Wk-45092	–	5	From left bank of river
	44,414 ± 978	Wk-92195	–	2	From right bank of river
6	43,506 ± 980	Wk-38671	–	4	From left bank of river
	41,321 ± 740	Wk-39014	–	4	From right bank of river
7	>50,000	NTU-5500	–	5	
8	2601 ± 26	Wk-38672	2750–2740	3*	
9	41,730 ± 701	Wk-42196	–	17	From left bank of river
	42,794 ± 641	Wk-42197	–	7	From left bank of river
	41,935 ± 799	Wk-42198	–	3	From right bank of river
	43,000 ± 936	Wk-42199	–	2	From left bank of river
	5704 ± 20	Wk-44097	6500–6450	>20	Sample in a block of debris-flow gravel on modern debris slope
	6053 ± 26	Wk-33187	6950–6860	>20	Sample on modern debris slope
10	41,452 ± 882	Wk-38673	–	7*	From right bank of river
	5678 ± 41	Wk-38674	6490–6410	10*	From left bank of river
	5670 ± 41	Wk-39015	6490–6410	8*	From left bank of river
	5721 ± 25	Wk-39016	6550–6470	8*	From left bank of river
11	888 ± 42	Wk-38675	900–740	–	Sample in a block of debris-flow gravel on modern riverbed
12	46,295 ± 1785	Wk-38676	–	–	Sample in a block of debris-flow gravel on modern riverbed
13	380 ± 40	NTU-5806	500–330	1	
14	47,423 ± 2820	Wk-41065	–	~200*	
	>45,000	NTU-5098	–	~193*	
	>50,000	NTU-5819	–	~180*	
15	>1950 CE	NTU-5809	–	15*	
16	>1950 CE	NTU-5837	–	50*	From slack-water sand deposited when the river was dammed
17	>1950 CE	NTU-5816	–	20*	

^a Sample site number referred to Fig. 7.^b Sample number assigned at dating laboratory; NTU = National Taiwan University; Wk = the University of Waikato.^c Dates <7 ka are calibrated (1σ range) using programme Calib Rev. 7.0.4 (Reimer et al., 2013).^d Sample height relative to local tributary riverbed or to the trunk riverbed (asterisked).

northward migration of the river to successively widen the hillslopes. The expansion of Surfaces S1 and S2 must have caused the retreat of the Tashan cliff, which concords with the presence of a truncated valley on the top of the cliff (Fig. 3). Nearly vertical joints parallel to the trunk Alishan River helps maintain the steepness of the cliff by rock fall and/or

toppling. Apparently, mass movements occurring at this side of the valley were relatively small and had limited influences on the lateral migration of the river, compared with the dip-slope failures on the opposite side, resulting in the overall asymmetric shape of the valley.

We believe that processes similar to those inferred above also operated in the Tsengwen River valley. Accordingly, through the northward trimming of the trunk Tsengwen River, Surfaces S3, S4, and S5 are likely to have been narrowed over time (Fig. 3). However, unlike the Taishan cliff, the cliff separating the S1 from the S3/S4 surfaces, along with the east-striking linear escarpments crossing S4 and S5, show no evidence of river cutting (Fig. 3). Therefore, these steep slopes could all originate from landslides or gravitational faulting following the nearly vertical, valley-parallel joints that prevail in the region. How these landslides (or faults) moved and their significance upon the formation of Surfaces S3, S4, and S5 remain unclear. Nevertheless, given that lateritic soils/colluvium were only found at this side of the ridge but not at the opposite side facing the Alishan River, the former hillslope appears to have been more geomorphically stable than the latter (i.e., the landslides or faults mentioned above might have been inactive for a long period of time).

5.3. Downward river incision

Rivers incised after the formation of the studied gentle, hummocky surfaces. The downstream increase in the heights of Surfaces S1 and S2 above the Alishan River indicates that the lower-middle part of the river has incised more rapidly than its upper part since the abandonment of the surfaces (Fig. 10). This is also true for bedrock, as its local heights exhibited along the river also increase in the downstream direction, especially along the waterfall (WF) upstream of the junction with Tributary C (Fig. 11d). Notably, no bedrock has been exposed

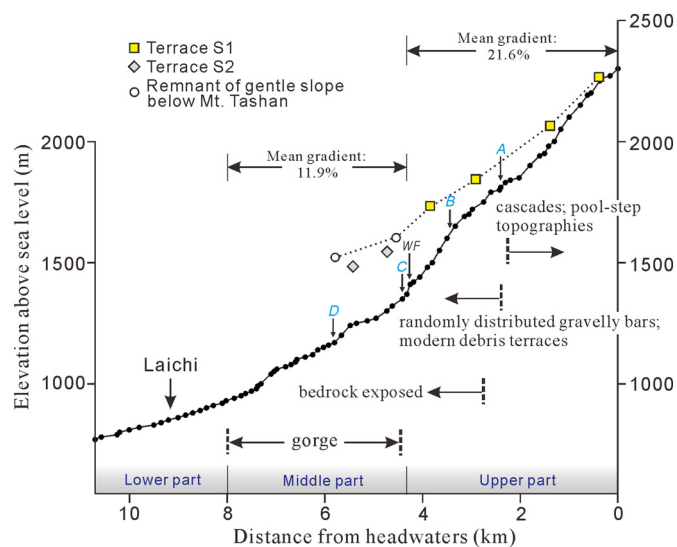


Fig. 10. Longitudinal profile of the Alishan River from headwaters to Laichi, based on 40-m mesh DEM issued by the Ministry of the Interior (based on data around 1980s). Sedimentary/topographic features are summarized. The outer edges of Surfaces S1 and S2, and the inner edges of the gentle-slope remnants shown in Fig. 7 are also projected.



Fig. 11. Topographies of the Alishan River. All taken in the summer of 2012 or in early 2013. (a) Step-pool topography along the uppermost part of the river above the junction with Tributary A. (b) Piles of giant boulders upstream of the mouth of Tributary A. Boulders are generally >2 m and up to several meters in diameter. (c) Deep valley around the mouth of Tributary B, which forms a waterfall ~50 m high. Arrow points to the trace of bedrock bedding plane below colluvium. (d) Waterfall (pointed) upstream of the junction with Tributary C. (e) Gorge downstream from the junction with Tributary C (facing downstream). (f) Remnant of gentle, colluvial slopes (pointed) above the gorge (see also Fig. 7 for location). Viewed from Erhwanping landslide.

along much of the upper part of the Alishan River, which yields a zero bedrock incision rate averaged over the past 40 ka, according to our dates (Sites 8 and 10; Fig. 7).

We attribute the observed spatial contrast in river incision rate to the contrast in landslide/debris-flow activities. Specifically, the lower-middle part of the Alishan River catchment is likely to have undergone more active landslides/debris flows than the upper part of the catchment. Debris flows are known as agents in eroding bedrock (e.g., Stock and Dietrich, 2006; Hsu et al., 2008; De Haas and Van Woerkom, 2016). Also, both theoretical and experimental studies have shown that significant fluvial bedrock incision can only occur where sufficient amounts of bedload sediments can act as saltation-abrasion tools for the incision (Sklar and Dietrich, 2001, 2004). As landslides/debris flows are the major sources of bedload sediments, the activity of landslides/debris flows (and the characteristics of the clasts they yield) poses strong controls on bedrock river incision, as simulated by Egholm et al. (2013). A positive feedback mechanism might have been involved because once a river rapidly incises, it destabilizes hillslopes (e.g., causing “daylight” of bedding planes), which in turn promotes landslide/debris-flow activities and the yield of bedload sediments for erosion.

Our inferred spatial contrast in mass-wasting activity is supported by modern observations, as during the 2009 typhoon nearly all tributaries (including C and D) joining the lower-middle part of the trunk Alishan River (but only Tributary A in the upper part) yielded debris flows. The greater activity of landslides/debris flows in the lower-middle part of the Alishan River catchment must have caused greater local erosion, which is consistent with our interpretation that Surface S2 has been lowered more rapidly than S1. In fact, the erosion of Surface S2 would contribute many landslides/debris flows (e.g., the 2009 Erhwanping) to the trunk river downstream from the junction with Tributary C. This satisfactorily explains why Waterfall WF, a result of differential bedrock incision, is located immediately upstream of the junction with Tributary C.

The strong coupling between landslides/debris flows and river morphology can further be viewed in the landscapes along the uppermost part of the Alishan River upstream from the junction with Tributary A. This part of the river, lacking recent landslides/debris flows and having experienced inactive bedrock incision over the past 40 ka, is characterized by cascade or step-pool topographies formed by rounded, moss-veneered large boulders (Fig. 11a). These boulders appear to have been placed by rock falls or landslides a long time ago, with more recent



Fig. 12. Colluvium exposed along the Alishan River (for location see Fig. 7). (a) Colluvial gravel ~50 m thick underlying Terrace T (Site 9). Yellow arrow points to the boundary between the lower, greyish gravel (massive) and the upper, greyish/yellowish gravel (stratified). (b) A typical view of the lower greyish gravel in (a), with a piece of non-carbonized tree trunk (dated $41,935 \pm 799$ BP). (c) Greyish gravel exhibited downstream of the junction with Tributary A (Site 10; left bank). (d) Greyish gravel exposed along Tributary D (Site 14).

prevailing fluvial forcing inadequate to emplace them. The significant increase in the sizes of the boulders approaching the junction with Tributary A is due to the contribution of extremely coarse clasts from Mt. Datashan. The accumulation of these giant boulders steepened the trunk river and caused the water to flow underground (Fig. 11b). We believe that these boulders can only be efficiently moved, and bedrock incised, by rare debris-flow events like those emanating from Tributary A during the 2009 typhoon. In fact, with a gentler slope and higher river flows, Tributary A was easily mistaken for the trunk river in the field.

5.4. The influence of glacial-interglacial climate change

We have detected a temporal change in river/hillslope processes in the Alishan area. The alternation of hillslope erosion and deposition has resulted in the deposition of thick colluvial sediment overlying bedrock bedding planes. The episodic nature of downward river incision created the landscape's gentle surfaces juxtaposed with steep slopes. Note that the uppermost part of the Alishan River, fringed by the ~700-m high Tashan cliff, has not been actively incised in the past 40 ka or longer. To compensate for this morphological deficit, the river must have incised extremely rapidly before the formation of Surfaces S1 and S2. The temporal change in the stability of the landscape is also shown by the presence of reworked lateritic soils/gravels on hillslopes. The minimum time period required for the development of lateritic soils, as constrained by dates obtained elsewhere in Taiwan, has been inferred to be 30–20 ka (Ota et al., 2002; Tsai et al., 2016). Our observed lateritic soils/gravels in Alishan, which show much greater degree of lateralization than the 30–20 ka deposits, are likely to have been developed for more than several tens of thousands of years. In other words, before the emplacement of these heavily-weathered materials on hillslopes, the study area had been geomorphically stable for at least several tens of thousands of years, a time span consistent with the radiocarbon dates.

The chronological data mentioned above reveal that the detected changes in the mode/rate of river/hillslope processes occurred at a time scale of several tens of thousands of years. No evidence suggests a change in tectonic/seismic activities during this time span. It is more likely the observed varying geomorphic processes reflect the contrast between the glacial and interglacial climate conditions. Like the monsoon-controlled paleoclimate in East Asian (e.g., An, 2000; Maher, 2016), the glacial climate in Taiwan is characterized by cool and dry conditions, compared with the climate during the interglacial and post-glacial (Holocene) periods (Liew et al., 2006). We propose that the thick colluvial deposits exposed in the study area were deposited in the last-glacial time when the drier climate resulted in a low frequency of landslides/debris flows and low river erosion/transport capability. In contrast, during the wet inter-/post-glacial periods characterized by more frequent heavy rains, rivers were able to flush out most of the sediment eroded from hillslopes (by both fluvial and debris-flow processes), in conjunction with rapid downward incision that steepened hillslopes and enhanced the potential for mass wasting (Fig. 14).

The characteristics of river/hillslope processes during the inter-/post-glacial periods in Taiwan can be determined through observation of modern environments. Only some extremely large heavy rainfall events triggered large-scale landslides/debris flows. Other heavy rains that did not cause significant hillslope erosion generated floods that scoured river banks and removed sediments deposited during former slope failures. Because of this, only a few mass-wasting events could have their stratigraphic/morphological evidence survive for more than a decade. Not surprisingly, only limited Holocene fluvial and mass-wasting records were found in the study area.

The monitoring of modern fluvial morphological changes in Taiwan shows that torrents generated by heavy rains are capable of incising bedrock at rates up to centimeters per year (Hartshorn et al., 2002) or even meters per event (Cook et al., 2013), through conveying sufficient bedload sediment. Dating of Holocene river terraces also yields bedrock



Fig. 13. Young sediments exposed along the gorge part of the Alishan River and around Landslide Y (for location see Fig. 7). (a) A distant view of a toppled log (indicated by arrow), which is included in a bed of slackwater sand stranded ~50 m high above the valley bottom (Site 16). Two people are circled for scale. (b) An upward view of a >50-m thick colluvial sequence at Site 17. A person is circled. (c) Greyish colluvial gravel exposed along the eastern flank of Landslide Y. (d) Landslide Y, taken on January 2013. LD = landslide deposit. DT = debris terrace constructed by debris flows generated during 2009 Typhoon Morakot. Arrow points to the location of the profile in (c).

incision rates up to a few centimeters per year (Schaller et al., 2005; Hsieh et al., 2014). All these rates are apparently higher than the contemporary tectonic uplift rates. We believe that the Holocene bedrock incision rates along the lower-middle part of the Alishan River, especially the gorge area, are no lower than the values mentioned above, considering that this relatively steep river reach has been incised by not only fluvial but also debris-flow agents.

Our work indicates that in contrast to the modern environment, heavy rainfall along with landslides/debris flows occurred relatively infrequently under glacial conditions in Taiwan. We suggest that during this period, and especially between landslide/debris-flow events, rivers typically had insufficient power to convey or erode sediment residing on riverbeds or along banks. This condition was enhanced, and the residence time of sediment increased, where landslides/debris flows supplied oversized boulders to protect riverbeds, as shown along the uppermost part of the Alishan River. We believe this low river competence (and thus mobility) explains why sediment transported by each

landslide/debris flow, even though uncommon, was able to progressively accumulate in valleys during glacial times.

5.5. Implications for the genesis of low-relief, high-elevation topographies

The formation of low-relief surfaces in non-glaciated mountains requires long-term cessation of river downcutting, during which river planation and/or hillslope degradation dominated. Emphasizing the acceleration of river downcutting that stranded the low-relief surfaces in high mountains suggests a rejuvenation of tectonic uplift following the formation of the surfaces (e.g., Davis, 1899). Underlining the slowing of river downcutting that started the formation of the surfaces in already-rugged mountains implies a decrease of drainage areas due to river piracy, in a condition of consecutive tectonic uplift (Yang et al., 2015). This study, however, provides alternative thinking. We have shown that the Alishan surface, one of the broadest low-relief, high-elevation surfaces in the Taiwan orogen, has been created in the past

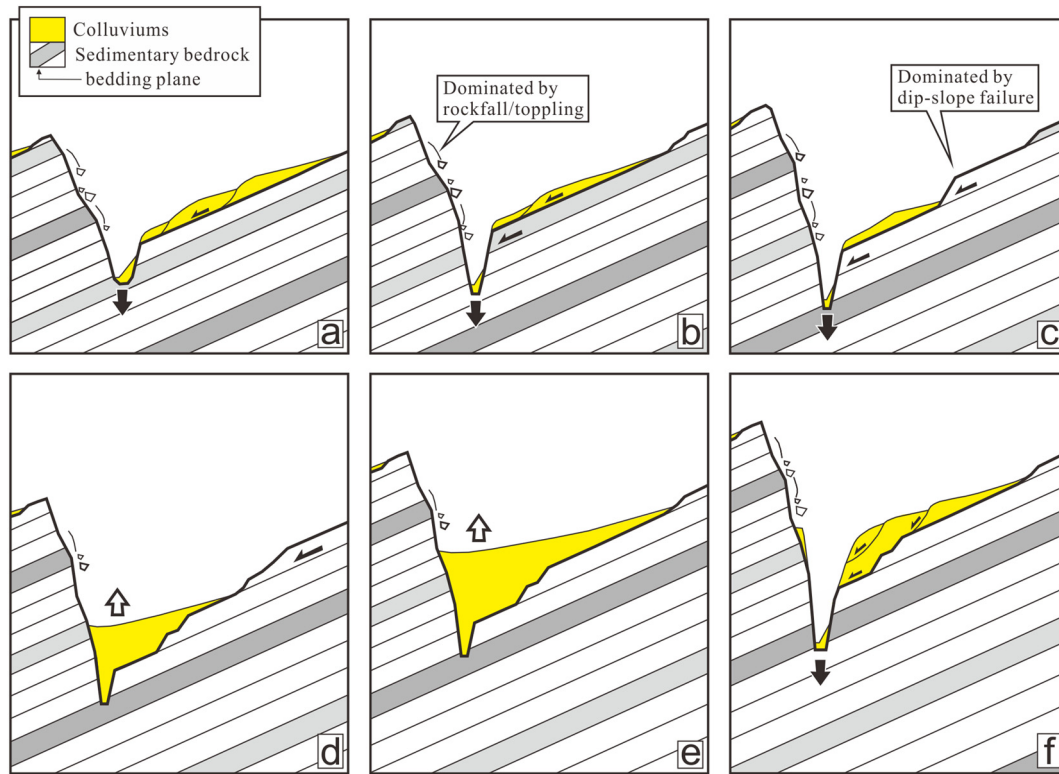


Fig. 14. Schematic diagrams showing the inferred temporal change in river/hillslope processes in the study area undergoing tectonic uplift. (a–c) During the wet last-interglacial period. Downward river incision dominated and most sediments yielded from hillslopes were able to be conveyed downstream. (d, e) During the dry last-glacial period. Valley aggradation dominated due to low erosion/transport capacity of rivers. (f) During the wet postglacial period. Rapid river incision resumed and the previously accumulated colluvium started to be flushed out of valley.

several tens of thousands of years. Over this time period, our observed change in the river-downcutting rate apparently overwhelmed any change of tectonic rates. No evidence of river piracy is shown in the studied landscapes. Also, the extensive colluvial aggradation that formed the Alishan surface could hardly be justified simply by the stability of tectonism or river piracy. Combination of these arguments suggests that the creation of this surface relates to glacial/interglacial climate change, an interpretation similar to that proposed by Oguchi et al. (2001) to explain the common downslope steepening of hillslopes in the mountains of Japan which have tectonic and geomorphic settings like Taiwan.

A key aspect of our interpretation is that over the time span of several tens of thousands of years, downward river incision was mainly controlled by the frequency of landslides/debris flows and their supply of bedload sediments serving as tools for fluvial erosion. When the activity of landslides/debris flows was significantly lower, river downcutting slowed down or even stopped, which facilitated the formation of low-relief surfaces, even though the overall landscape was progressively raised by tectonic uplift (Fig. 14d, e). In contrast, with frequent landslides/debris flows, river downcutting significantly exceeded tectonic uplift, favoring the formation of steep hillslopes (Fig. 14a–c). We argue that in the time scale indicated by this study, the landslide/debris-flow activity and its influences on river processes can readily be governed by climate forcing (e.g., magnitude/frequency of severe rains) without the necessity of tectonic change or river network reorganization (e.g., river piracy).

We have suggested that the low-relief, high-elevation surfaces in Taiwan were created during periods of low river mobility. Under this condition, the surfaces are expected to have been shaped mainly by hillslope degradation, which could vary from place to place in types/magnitudes, controlled by bedrock lithology and structures. In Alishan, the broadness of both the Tashan and Alishan surfaces apparently

reflects the hardness and gentle dipping of the Kuantoushan sandstone and Nanchuan formation, whose dips also determine the gradients of the two surfaces. The Alishan surface, steeper and composed of more shale bedrock (Fig. 2), appears to have had greater potential for large-scale dip-slope failures than the Tashan surface. It is through the extensive deposition by this type of mass movement that we were able to obtain datable materials to constrain the age of the surface and to shed light on the nature of the low-relief, high-elevation surfaces in the orogen generally.

6. Conclusion

We have shown that at least parts of the gentle surfaces stranded in Alishan are capped by mass-wasting gravels 60–100 m thick and dated >50 ka to 40 ka BP. These thick colluvial deposits overlie surfaces composed of bedrock bedding planes dipping $\leq 30^\circ$, apparently exposed by dip-slope failures. We propose this phase of hillslope erosion occurred during the wet last-interglacial period when rivers were capable of conveying most of the sediment eroded from hillslopes, in conjunction with rapid incision facilitated by frequent debris flows and sufficient bedload sediments serving as tools for fluvial erosion. In contrast, during the dry last-glacial period the low erosion/transport capacity of rivers allowed the progressive deposition of thick colluvium on the preexisting, relatively gentle bedrock bedding surfaces. It was not until the postglacial period that frequent slope failures with rapid river incision resumed, and the previously accumulated last-glacial colluvium started to be flushed out of valleys.

This study demonstrates that the formation of one of the broadest gentle surfaces in the high mountains of Taiwan was strongly governed by glacial-interglacial climate change superimposed on long-term tectonic uplift. This conclusion provides a basis for future studies on erosion, sediment transport/residence histories, and the genesis of

other low-relief, high-elevation topographies in the orogen in response to both tectonic and climate forces.

Acknowledgements

This research was sponsored by the Ministry of Science and Technology, Taiwan (MOST 106-2116-M-194-014-010). We thank Dr. Lucas Mesalles in National Chung Cheng University for his valuable comments on the manuscript. Gratitude also goes to Mr. Yu-Da Xiao, Mr. Xiu-Guo Cui, Mr. Yi-Ho Tseng, and Miss Wan-Lin Hu from National Chung Cheng University for their kind help in the field survey.

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